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OPTIMUM TRANSMISSION RATE FOR LOW POWER METEOR BURST COMMUNICATIONS SYSTEMS

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By: [redacted]

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This is a preliminary, un-edited, rough draft for purposes of review only. It is not to be published in any form.

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Introduction

Reliable low power communications systems have recently been demonstrated which operate in the VHF range out to distances of 1300 miles. These systems transmit intelligence intermittently by reflecting radio signals from suitably oriented, ionized trails, which are left in our upper atmosphere by disintegrating meteors. The characteristics of such a propagation mode make meteor burst systems particularly attractive in mobile applications where severe penalties are imposed on equipment size, weight, and power demands.

Questions which the mobile communications system designer invariably asks are:

1. How much traffic can meteor burst systems pass?
2. What frequency ranges are usable?
3. What are the bandwidth limitations?
4. What error rates can be achieved?
5. What is the reliability of the mode?
6. What transmitter powers and antennas are needed for a given capacity?
7. What sort of modulation distortion might be expected?
8. How does the capacity of the system vary with system parameters?

The initial answers to these questions, based on theoretical meteor model analysis and back scatter radar experiments were:

1. Usable energy propagated on a communications circuit would vary inversely as approximately the third power of frequency.
2. More information could be passed by transmitting at high speeds and using wide transmission bandwidths.
3. The error rate of the channel could be easily controlled by adjustment of the transmission decision threshold level.

4. The outage time of the channel would be greatly improved due to the higher operating frequencies possible.

5. Amplitude and phase of the received signal could be expected to be relatively stable during a burst.

6. Most useful meteor trails would be located off the direct path between the transmitter and receiver. The size of this useful meteor area in the sky indicated that perhaps narrow beam antennas would not significantly increase the capacity of the system.

Now, after actual on-the-air experience with meteor burst communications systems and collection of pertinent data, a more complete answer to some of these questions can be given. The system parameter which will receive the most attention in this paper is the role of transmission rate or system bandwidth in the capacity of a meteor burst system. An optimum bandwidth theory is presented, based on an equal contribution from "underdense" and "overdense" meteor trails. Such a criterion implies that the best bandwidth is directly dependent on other system parameters, such as transmitter power, antenna gains, threshold power level, etc. For a low power system this optimum bandwidth may be quite low.

Information Capacity of Intermittent Channel

In a communications channel the average rate of information transfer is proportional to the average transmission rate if this rate does not exceed the theoretical capacity of the channel, and if the redundancy transmitted and the error rate of the received transmission are constant. In a simple on-off, intermittent, communications system this average information rate (I_{av}) is:

$$I_{av} = (\vartheta)(R)(d.c.) \qquad (1)$$

where ϑ is the factor taking into account the loss of information from transmission redundancy and received errors.

R is the instantaneous transmission rate

d.c. is the average duty cycle (the fraction of the total time at which information is transmitted at the instantaneous rate).

Bandwidth vs. Instantaneous Rate

In a binary channel the transmission bandwidth required (B), is a direct function of the transmission rate and can be expressed as:

$$B = nR \qquad (2)$$

The factor (n) is a constant depending on the modulation and detection scheme. The minimum theoretical value of (n) is $\frac{1}{2}$, that is, two independent bits of information can be transmitted and detected for every cycle of bandwidth. Practical modulation and detection schemes fall somewhat short of this ideal, however, and a more realistic figure would be a value of (n) equal to about 2.

Some Theoretical Considerations - Duty Cycle -

In fixed-rate, on-off, meteor-burst systems, information will be transmitted only when the received signal exceeds a given threshold signal-to-noise ratio. The integrated time of these signals can be defined as the product of the number of times the signal exceeds the threshold power level and the average duration of each signal above this threshold.

The number of meteor signals received which exceeds a threshold counting level is related to the initial electron line density of the meteor trail (q) and to the meteor reflection geometry. The initial line density of the trail is in turn directly proportional to the mass of the disintegrating meteor. The number-mass distribution for meteors disintegrated in the earth's atmosphere per unit time is inversely related to the original mass of the meteor (approximately). Therefore this same distribution can be used for the number of trails which exceeds a given line density (q_o). That is:

$$N(q > q_o) = A\, q_o^{-1} \tag{3}$$

Not all meteor trails above the threshold line density reflect usable signals to the desired receiver. Stringent geometric conditions of the trail relative to the transmitting and receiving terminals must be met also. This fact can be included in the constant (A) so that this number will be interpreted to mean the number of trails with initial line densities greater than q_o also reflecting signals between two terminals.

Received Energy

The energy received from a meteor trail will be governed by the one of two reflection models which best suits the particular trail. The two models, so-called "underdense" and "overdense" trails, are distinguished by their initial electron line densities.

The underdense trail model, which is defined as trails with initial line densities less than approximately 10^{14} electrons per meter, has a theoretical peak received power (P) given by:

$$P_u = K_u\, P_t G_t G_r \lambda^3 q^2 \tag{4}$$

where P_t is the transmitted power,

G_t and G_r are the transmitter and receiver antenna gains respectively,

K_u is a constant depending upon path geometry and polarization.

For trails with initial electron line densities greater than 10^{14} electrons per meter (overdense trails) the peak received power P_o is believed to vary according to the relation:

$$P_o = K_o P_t G_t G_r \lambda^3 q^{\frac{1}{2}} \qquad (5)$$

where K_o is again a constant depending on path geometry and polarization.

The duration of underdense trails depends on the time required for a sufficient number of electrons to disperse to the distance where scattering of the impinging radio wave by the electrons is incoherent. The time will be a strong function of the transmitted frequency and can be expressed approximately as:

$$D_u = \gamma_u \lambda^2 \qquad (6)$$

where γ_u is a constant depending upon path geometry and diffusion rate of the trail. The duration is usually about 200 to 300 milliseconds. The average duration of overdense trails is theoretically longer than that of underdense trails but the actual signal may be shorter. This is brought about by the fact that wind distortion of the trail usually takes place causing multipath interference which breaks up the received signal into a series of short bursts. As a first approximation it will be assumed that the average duration is also directly proportional to the square of the wavelength.

If the threshold power level is sufficiently low in comparison to the power level corresponding to an initial line density of 10^{14} electrons per meter, then the vast majority of the trails detected will be of the underdense type. In this case the duty cycle $d.c._u$ can be expressed approximately as:

$$d.c._u = K_a \left[\frac{P_t G_t G_r \lambda^3}{P_r} \right]^{\frac{1}{2}} \lambda^2 \qquad (7)$$

The constant K_a is the result of lumping various other constants together and then integrating over the common illuminated meteor area.

For thresholds corresponding to initial line densities higher than 10^{14} electrons per meter, all of the trails are of the overdense variety and the duty cycle is approximately:

$$d.c._u = K_b \left[\frac{P_t G_t G_r \lambda^3}{P_r} \right]^2 \lambda^2 \qquad (8)$$

where K_b is again an integrated constant over the illuminated meteor area.

Illuminated Meteor Area

One additional effect needs to be considered. The duty cycle in each of the above cases depends on the integration over the meteor plane area commonly illuminated by the antenna systems of each terminal. Hence, the values of K_a and K_b will actually be a function of the antenna gains. For convenience then, these factors (K_a and K_b) will be divided into three parts; one of which is independent of antenna gain, and two others which are independent functions of the receiving and transmitting antenna gains. That is:

$$K_a = K_a' \, G_t^{-a_t} \, G_r^{-a_r} \qquad (9)$$

$$K_b = K_b' \, G_r^{-a_t} \, G_r^{-a_r} \qquad (10)$$

The factors K_a' and K_b' are now considered truly constant for a particular path and time. The "discrimination factors" (a_t and a_r) relate the size and location of the area illuminated by the antenna to the size and location of the most useful meteor contribution for the particular path and time. For correctly oriented antennas with gains below about 8 db, these "discrimination factors" are essentially zero since very few useful meteors occur outside the beamwidth of such antennas.

Required Threshold Power

To maintain a minimum intelligibility over a burst communications circuit, the average signal received when information is transmitted must be above the noise signal received by a fixed ratio. The value of this signal-to-noise ratio depends on the intelligibility required and the type of modulation and detection schemes used.

When the message is transformed into a binary code, the intelligibility can usually be expressed in terms of received binary error rate. From this the required signal-to-noise ratio can be determined by assuming a modulation and detection scheme and a distribution of signal and noise powers. In this discussion it will suffice to say that the intelligibility can be expressed as a minimum signal-to-noise ratio $(^S/_N)$ required to transmit information over the circuit with the minimum required intelligibility. That is:

$$(^S/_N) = \frac{P_r}{P_n} \tag{11}$$

where P_r is the minimum received signal required,

P_n is the average noise power received.

<u>Received Noise Power</u>

The received noise power (P_n) is normally a direct function of the receiver bandwidth, this can be expressed as:

$$P_n = kTBF \tag{12}$$

where kT is a constant (4×10^{-21} watts/cycle),

B is the base bandwidth of the receiver,

F is the excess noise above normal thermal noise admitted to the receiver detector system.

For a receiver in the low VHF range when reasonable care in the selection of an antenna site and design of the receiver front-end stage has been taken, the noise factor can be considered predominantly cosmic-generated and is expressed approximately as:

$$F \quad A\lambda^{2.3} \tag{13}$$

where A is an arbitrary constant.

The noise power is:

$$P_n = kTBA\lambda^{2.3} \tag{14}$$

In some abnormally noisy locations it may be necessary to add an additional margin of safety to this figure.

<u>Information Capacity and System Parameters</u>

The previously derived results can now be combined to give a relation between information transfer and some of the pertinent system parameters. For low threshold levels where a predominance of underdense trails is used, the duty cycle expression is:

$$d.c._u = K_u \left[\frac{P_t}{RB}\right]^{\frac{1}{2}} \lambda^{2.35}\, G_t^{\frac{1}{2}-a_t}\, G_r^{\frac{1}{2}-a_r} \tag{15}$$

and for high threshold levels where only overdense trails are counted, the duty cycle is approximately:

$$d.c._o = K_o \left[\frac{P_t}{RB}\right]^2 \lambda^{3.4}\, G_t^{2-a_t}\, G_r^{2-a_r} \tag{16}$$

The factors K_u and K_o are the results of the lumping together of various other constants.

The average information rate, as previously defined in terms of duty cycle and bandwidth, can be written for the two types of meteor propagation models as:

$$I_{av_u} = nK_u \left[\frac{P_tB}{R}\right]^{\frac{1}{2}} \lambda^{2.35}\, G_t^{\frac{1}{2}-a_t}\, G_r^{\frac{1}{2}-a_r} \text{ for underdense trails} \tag{17}$$

$$I_{av_o} = nK_o \left[\frac{P_t}{R}\right]^2 \frac{1}{B} \lambda^{3.4}\, G_t^{2-a_t}\, G_r^{2-a_r} \text{ for overdense trails} \tag{18}$$

Some interesting observations can be made with regard to maximizing the information rate of a meteor burst system. If underdense trails are the predominate type of scattering mechanism, information transfered will increase:

1. Directly with the square root of the transmission bandwidth.

2. Directly with the square root of the transmitter power.
3. Inversely with the square root of the signal-to-noise threshold level.
4. Inversely with approximately the square of the operating frequency.
5. Directly with antenna gain until the "discrimination factor" becomes appreciable.

If overdense trails are the predominate mode, the information transfered increases:

1. Inversely with the transmission bandwidth.
2. Directly with the square of the transmitter power.
3. Inversely with the square of the signal-to-noise threshold level.
4. Inversely with frequency to approximately the third power.
5. Directly with the antenna gain for small "discrimination factors".

Sketches of this information transfer as a function of these parameters are shown in Fig. 1. The dotted lines show an estimation of the transition between the two discrete functions. Inspection of these sketches reveals that only the bandwidth gives a maximum information rate for a finite value of the parameter. This optimum bandwidth occurs in the transition region of underdense to overdense trails where the slope of the curve is zero.

If the bandwidth is adjusted to this optimum value then, for limited variations of the other parameters or if the bandwidth is readjusted to maintain the optimum, the information transfer in the transition zone is approximately:

$$I_{av} = K \frac{P_t}{R} \lambda^3 G_t^{1-a_t} G_r^{1-a_r} \qquad (19)$$

The exponents for the system parameters are simply an average derived from the underdense and overdense relationships.

Evaluation of Constants from Experimental Measurements

It is apparent from the myriad of unknown constants introduced in the previous discussion that a resort to some specific measured data must be made in order to proceed. Duty cycle is the propagation parameter most measured by meteoric propagation investigators. Unfortunately, this measurement is subject to wide variations which depend on both the time and location of the measurement and on the experiment instrumentation. The following evaluation will be based on duty cycle data obtained over the Bozeman-Palo Alto link during the early morning hours.

Fig. 2 shows a duty cycle vs. transmitter power curve obtained for 10 minute periods from 0400 to 0800 for a two-week period in December, 1958. The system parameters for the experiment were approximately as follows:

(S/N) = 17 db G_t and G_r = 7 db

B = 650 cps a_t and a_r = 0

Freq. = 40.4 Mc

Notice that the slope of this function does change from a value greater than one to a value less than one as the transmitter power increases. The estimated duty cycle and power where this occurs is approximately:

$d.c._1$ = 3% P_t = 120 watts

Optimum Duty Cycle

From Equations 4, 9, and 12 the duty cycle can be expressed in terms of the threshold line density (q_r) as:

$$d.c. = \frac{A \lambda^2}{G_t^{a_t} G_r^{a_r} q_r} \tag{20}$$

where (A) is considered a constant over the period of measurement and is a function of the meteor characteristic at a particular time and location, rather than of any system parameter. If the system is to be operated with an equal contribution from underdense trails and overdense trails the threshold line density (q_r) will be a constant (about 1×10^{14} electrons per meter). With a threshold level based on a specific ionization concentration the duty cycle will be independent of all system parameters except frequency and antenna gain when the "discrimination factors" are appreciable. An important rule-of-thumb can then be given for optimizing certain system parameters as follows:

"The optimum capacity duty cycle in a fixed-frequency fixed-antenna system is constant. Any system parameter change which alters the duty cycle from this value should be compensated by a corresponding change in another system parameter so that the duty cycle returns to its optimum value."

Notice also that this optimum duty cycle is inversely proportional to the square of the operating frequency. Therefore optimum duty cycles for higher operating frequencies can be expected to be much smaller than corresponding duty cycles at lower operating frequencies. For high gain antennas the optimum duty cycle may be reduced somewhat also. Evaluating the constant $\frac{A}{q_r}$ from the experimental data, an expression for the optimum duty cycle for these conditions is:

$$d.c._{opt} = \frac{\lambda^2}{G_t^{a_t} G_r^{a_r}} \tag{21}$$

Optimum Bandwidth

As long as the threshold line density is below 10^{14} electrons per meter the constant $(\frac{q_r}{K})$ may be expressed in terms of the system parameters from Equations 5, 14, and 17 as:

$$\left(\frac{q_r}{K}\right)^2 = \frac{B(^S/_N)}{P_t G_t G_r \lambda^{.7}} \qquad (21)$$

Evaluation of this constant from these experimental values gives:

$$\left(\frac{q_r}{K}\right)^2 = 2.64 \qquad (23)$$

and the optimum bandwidth for the system is then:

$$B_{opt} = 2.6 \times \frac{P_t G_t G_r \lambda^{.7}}{(^S/_N)} \qquad (24)$$

Information Capacity with Optimum Duty Cycle and Optimum Bandwidth

From Equations 1 and 2, the information transmission rate at the optimum bandwidth and duty cycle is:

$$I_{av} = \frac{\partial}{n} B_{opt} d.c. = 1.5 \times 10^{-3} \frac{\partial}{n} \times \frac{P_t}{(S/_N)} \lambda^{2.7} G_t^{1-a_t} G_r^{1-a_r} \qquad (25)$$

Here it is seen that the information rate is directly proportional to the transmitter power and inversely proportional to the frequency raised to the 2.7 power. Although the information capacity penalty is high when a high operating frequency is chosen, high operating frequencies are less susceptable to the severe ionospheric disturbances which plague the lower operating frequencies.

Notice also that the information rate can be improved by lowering the threshold signal-to-noise ratio. This could be done, still maintaining the same message intelligibility, by appropriate redundant coding of the message. The net improvement for any particular case would be determined by the ratio of $\partial/(^S/_N)$ where ∂ reflects the loss in transmission efficiency by the redundancy added.

Illustrative Examples

For purposes of illustration the information transfer for a specific system will be calculated. The system parameters are assigned values which might be typical for a burst system with a mobile transmitter station as follows:

$P_t = 50$ watts	$(S/N) = 13$ db
$G_t = 4$ db $(a_t = 0)$	Freq. $= 50$ Mc
$G_r = 13$ db $(a_r = .15)$	$\rho = .6$
	$n = 2$

The redundancy factor (ρ) in this case is meant to include only the non-message transmissions such as recognition signals, synchronization bits, etc., necessary in the transmission of a message in short bursts. Hence the information transfered represents the actual rate of message bits transmitted. The optimum duty cycle and antenna gain at this frequency would be only 1.3 percent. The optimum bandwidth would be 1200 cps which would represent a bit transmission rate of 600 bits per second. The average information rate would be 4.7 bits per second. A 100 word message (at 6 letters per word and 5 bits per letter) would take an average time of 11 minutes to be transmitted.

The curves of Figures 3, 4, and 5 give an indication of how the optimum bandwidth and certain system parameters vary with average information rate requirements.

It should be pointed out again that these curves are based on a limited amount of data taken on a particular path during an early morning operating time. System design for other times and paths would require additional propagation measurements. Also wide variations from the average can be expected for short operating times so that it would be well to incorporate a generous safety factor in design decisions based on such curves. As more propagation data is collected and analyzed, it will become possible to more accurately estimate the magnitudes of these deviations.

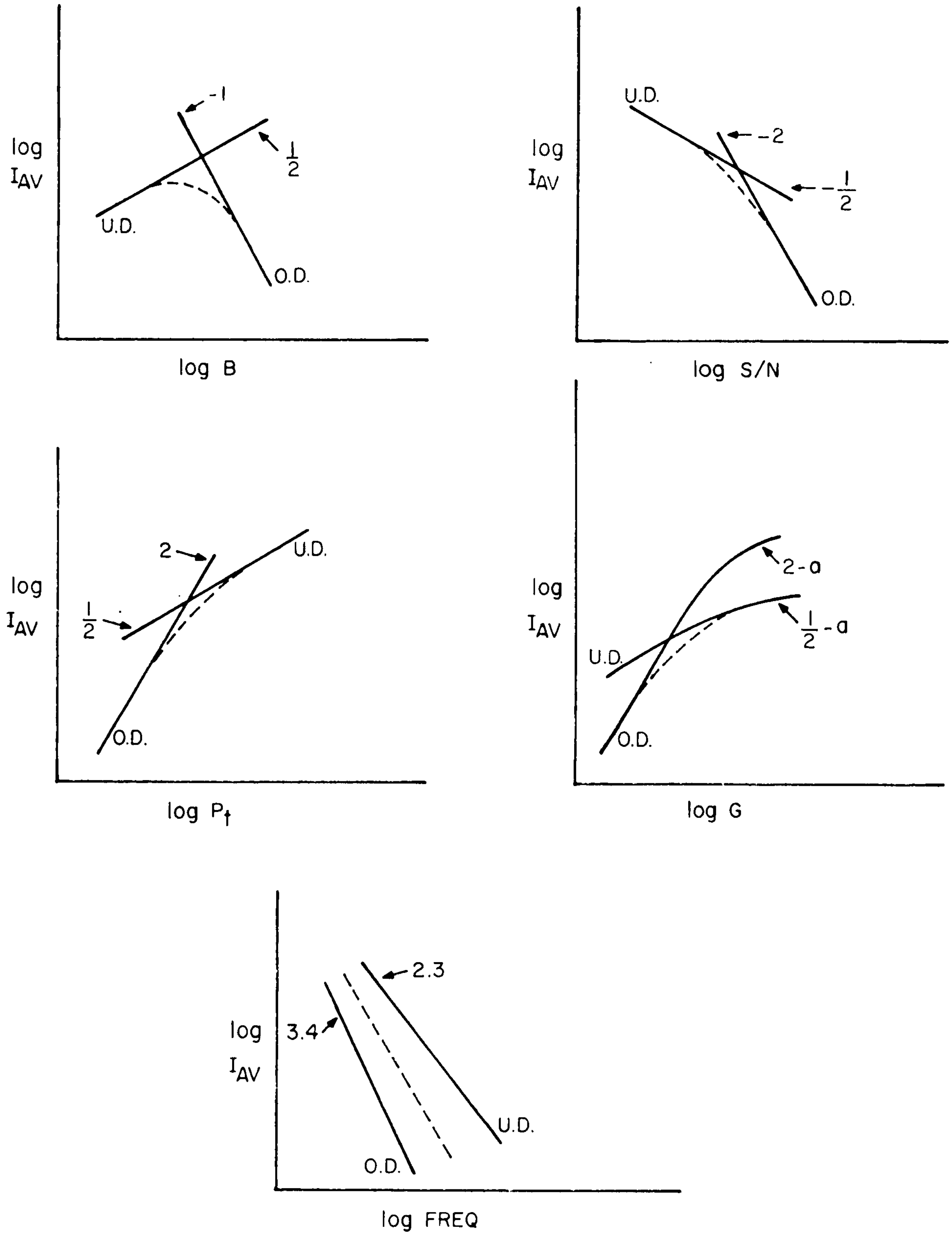

FIGURE 1

<u>**Sketches of Information Transfer Functions**</u>

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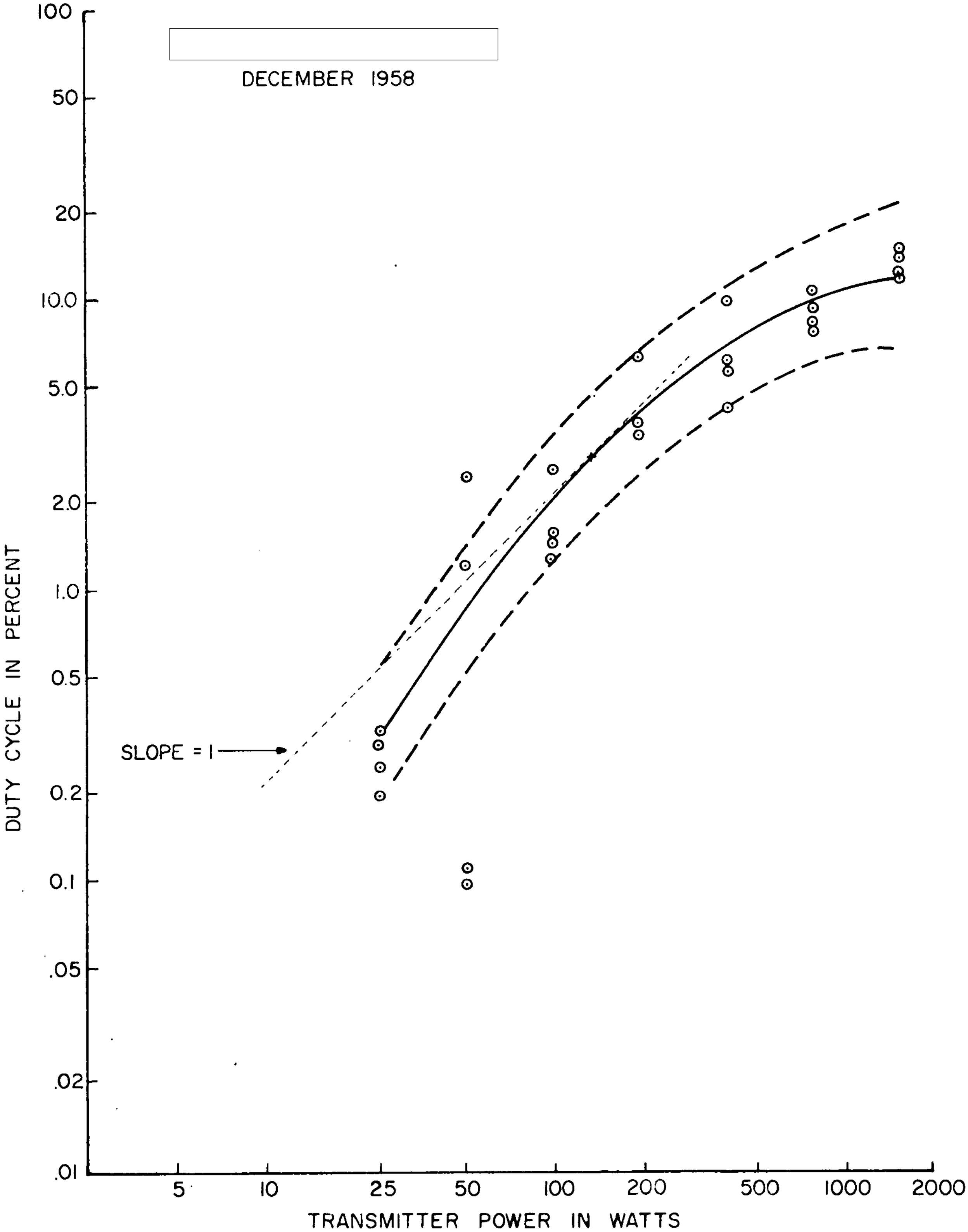

FIGURE 2

Duty Cycle vs. Transmitter Power

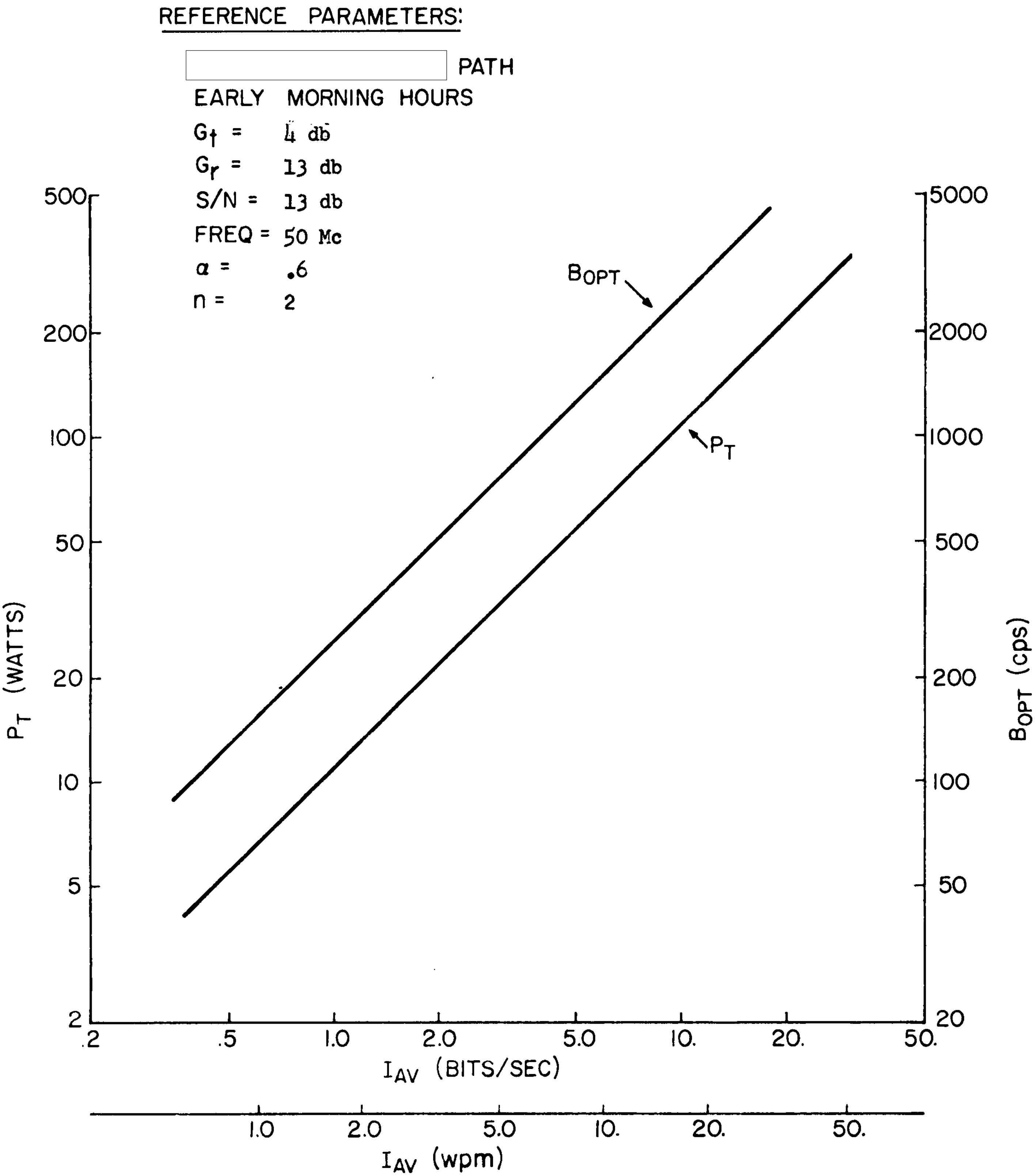

FIGURE 3

Optimum Bandwidth and Transmitter Power Required vs. Information Rate

REFERENCE PARAMETERS:

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EARLY MORNING HOURS

G_t = 4 db

G_r = 13 db

P_t = 50 watts

FREQ = 50 Mc

α = .6

n = 2

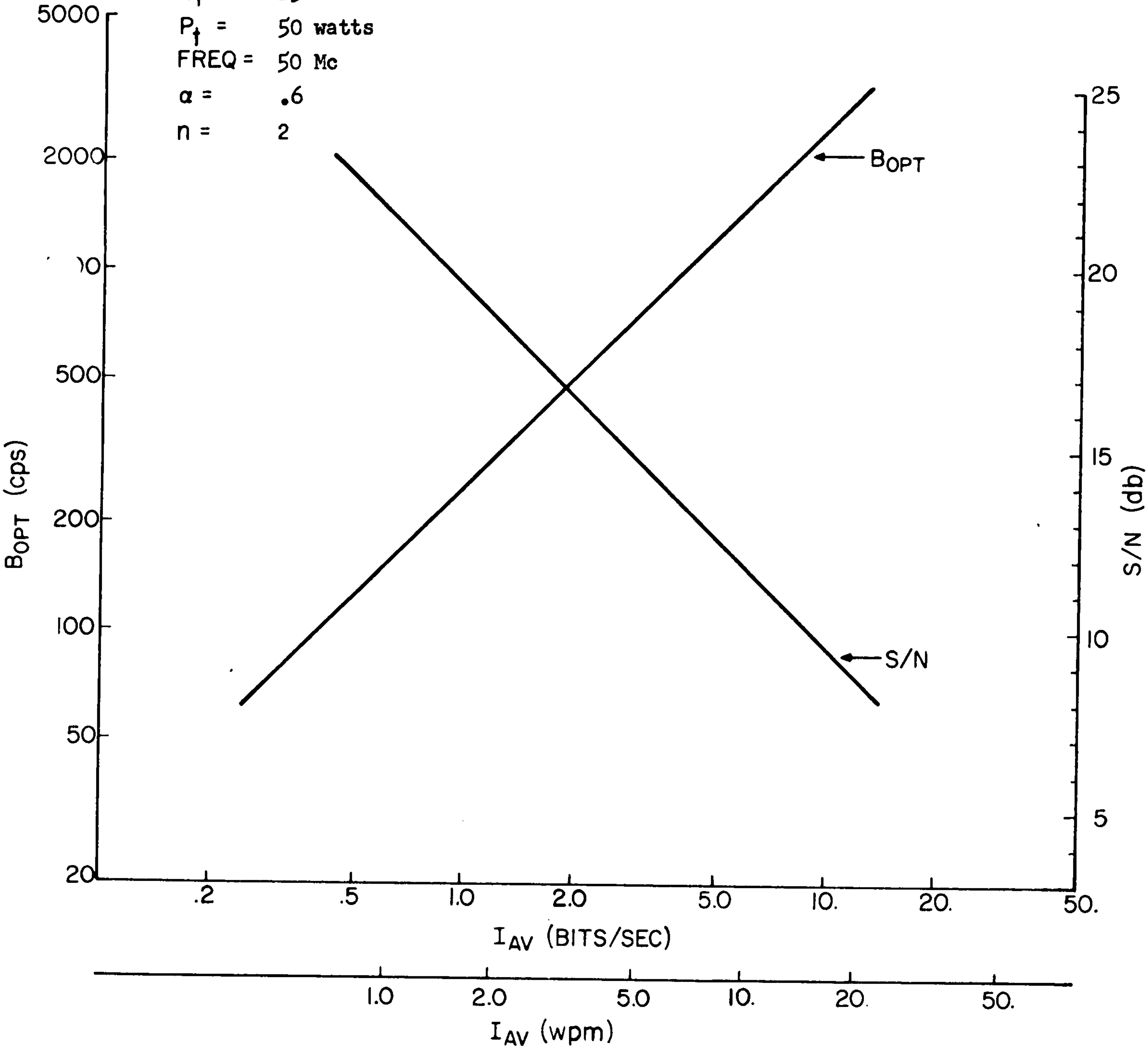

FIGURE 4

Optimum Bandwidth and Threshold Signal Power Required vs. Information Rate

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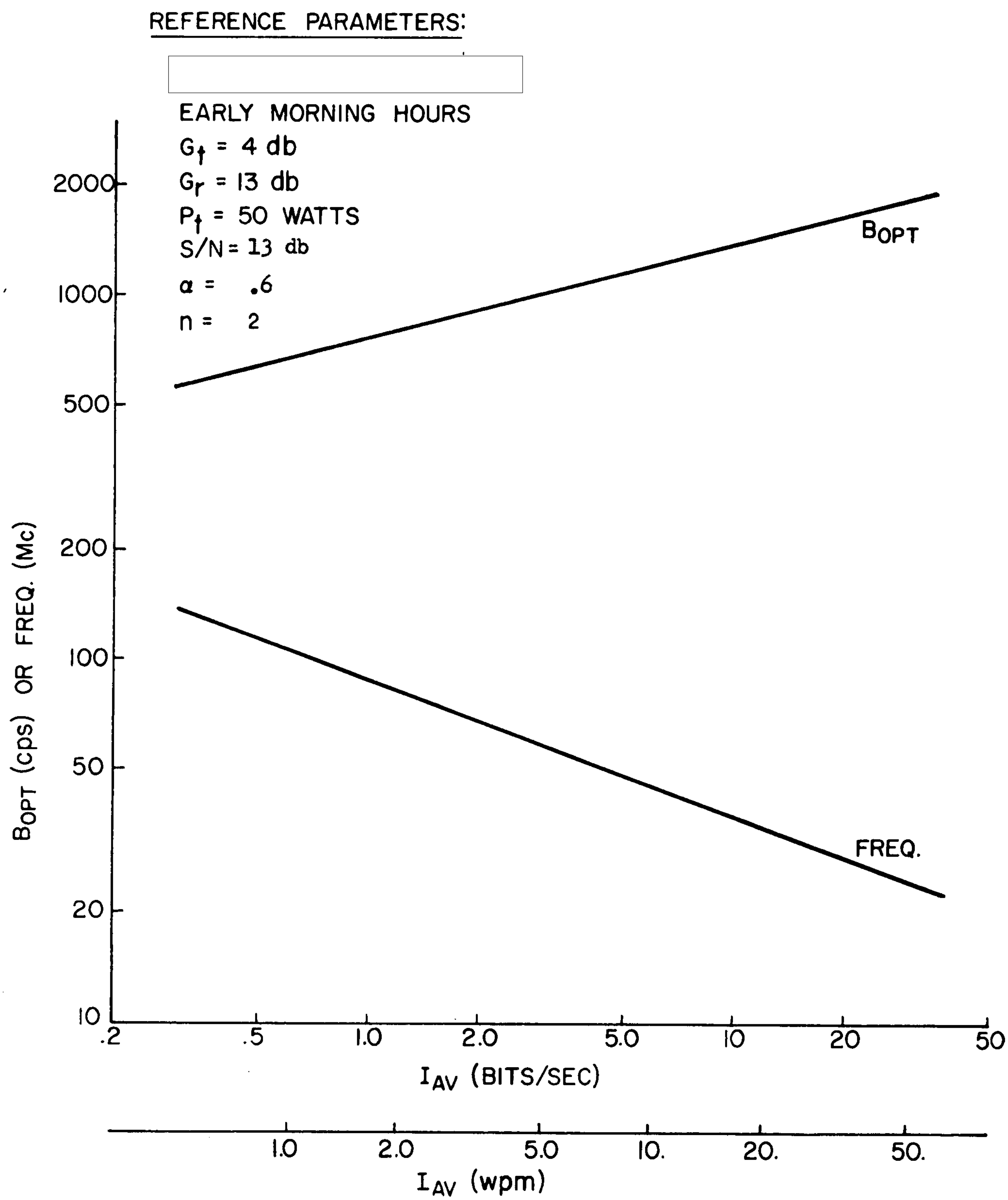

FIGURE 5

Optimum Bandwidth and Maximum Usable Frequency vs. Information Rate

April 24, 1959 25X1

[redacted]

Electronics Research Directorate

Dear [redacted] 25X1

The traffic handling capacity of meteor-burst communications systems has been a favorite topic of discussion among communications workers for the past few years. Considerable effort has been expended in collecting data to establish meteor-burst traffic capacity on your Contract AF 19 (604) 1517. Most of the parameters which affect the information-handling capability of meteor-burst systems have now been determined (although the precision of knowledge of some parameters is still inadequate) and it is now possible to arrive at estimates of this quantity for practical system designs.

The results of teletype capacity tests have been reported [redacted] 25X1
[redacted] These results along 25X1
with system design considerations reported in Scientific Reports 6, 8, and 11 and antenna design data which can be obtained from Scientific Report 12 show that by simple and inexpensive changes in the [redacted] 25X1
a daily average traffic handling capacity of 300 teletype words per minute (or 5 teletype channels) can be obtained. The system parameters for the present [redacted] installation are tabulated in Table I and the system parameters required to pass five teletype channels are tabulated in Table II. Note that the large increase in traffic capacity is obtained without changing the transmitter power of 2 kw. Additional refinements are possible beyond those listed in Table II. I do not intend to imply that 300 words of teletype is the ultimate limit for 2-kw transmitters. Table II is intended as an example to show what can be accomplished with practical, easy-to-engineer modifications. 25X1

It is quite apparent that low power meteor-burst systems have now reached the stage of competing with high power ionospheric scatter circuits in traffic capacity. This is primarily due to the inherent increase in efficiency in the utilization of the available signal obtained by the use of a control loop which permits traffic flow only during periods of good signal.

The control loop also provides a channel where error rate can be adjusted by a simple adjustment in decision level - a feature not possible in ionospheric scatter circuits where error rates are primarily caused by sharp signal fades (neglecting backscatter echoes) which can be improved only by increased transmitter power. The control loop also provides attractive features when operating under conditions of intentional or unintentional jamming.

Table I and II along with the accompanying illustrations have been placed letter form so that you may more quickly review our results. I am sorry that a traffic capacity estimate could not be made at an earlier date since this is of course the main factor required by communications planners. Accurate knowledge of the dimensions and movement of the meteor hot spot volume were required before efficient antenna designs and traffic handling estimates could be made. As you know, tests to measure the hot spot dimensions depended upon a cooperative experiment between your office and the [redacted] equipment in our field sites. This 25X1
equipment has only recently been available for the tests required. I am pleased that we can finally arrive at reasonable estimates on traffic capacity of meteor-burst systems.

It is our intent to cover more completely the topic of traffic capacity in additional scientific reports and in the final report of Contract [redacted]. Please feel free to inquire if the sketchy material in 25X1
this letter is not adequate for the needs of your laboratory and others interested in the topic.

Sincerely,

[redacted] 25X1
Communication Group

WRV:egm

Enc

TABLE I

OPERATING PARAMETERS FOR TELETYPE TRAFFIC CAPACITY TESTS,

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Transmitter power output	2 kw
Transmitter antenna	3-element Yagi
Transmitter frequency	40.38 Mc
Modulation	Frequency shift keying
Frequency deviation	2.5 kc
Transmission rate of teletype	600 wpm
Memory	Perforated paper tape
Receiver noise figure	2 db
Receiver noise bandwidth	1.3 kc
Decision level	16 db above noise
Receiver frequency	32.8 Mc
Receiver antenna	3-element Yagi

OPERATING PARAMETERS FOR TELETYPE TRAFFIC CAPACITY TESTS,

25X1

Transmitter power output	2 kw
Transmitter antenna	3-element Yagi
Transmitter frequency	32.8 Mc
Modulation	Frequency shift keying
Frequency deviation	2.5 kc
Receiver noise figure	2 db
Receiver noise bandwidth	1.3 kc
Receiver decision level	16 db above noise
Receiver frequency	40.38 Mc
Receiver antenna	3-element Yagi
Memory	Magnetic tape--1000-Character capacity Magnetic core--256 character capacity

TABLE II

PARAMETERS OF SYSTEM CAPABLE OF 300 TELETYPE WORDS PER MINUTE

Transmitter Power	2 kw
Transmitter antenna gain	11.5 db
Receiver antenna gain	11.5 db
Receiver antenna diversity	Dual
Frequency	40 Mc region
Modulation	Synchronous frequency shift keying
Coding to reduce errors	None
Receiver Noise Figure	3 db
Receiver bandwidth	1 kc
Receiver decision level	15 db above noise
Transmission rate during burst	600 W. P. M.

AVERAGE DAILY TELETYPE CAPACITY

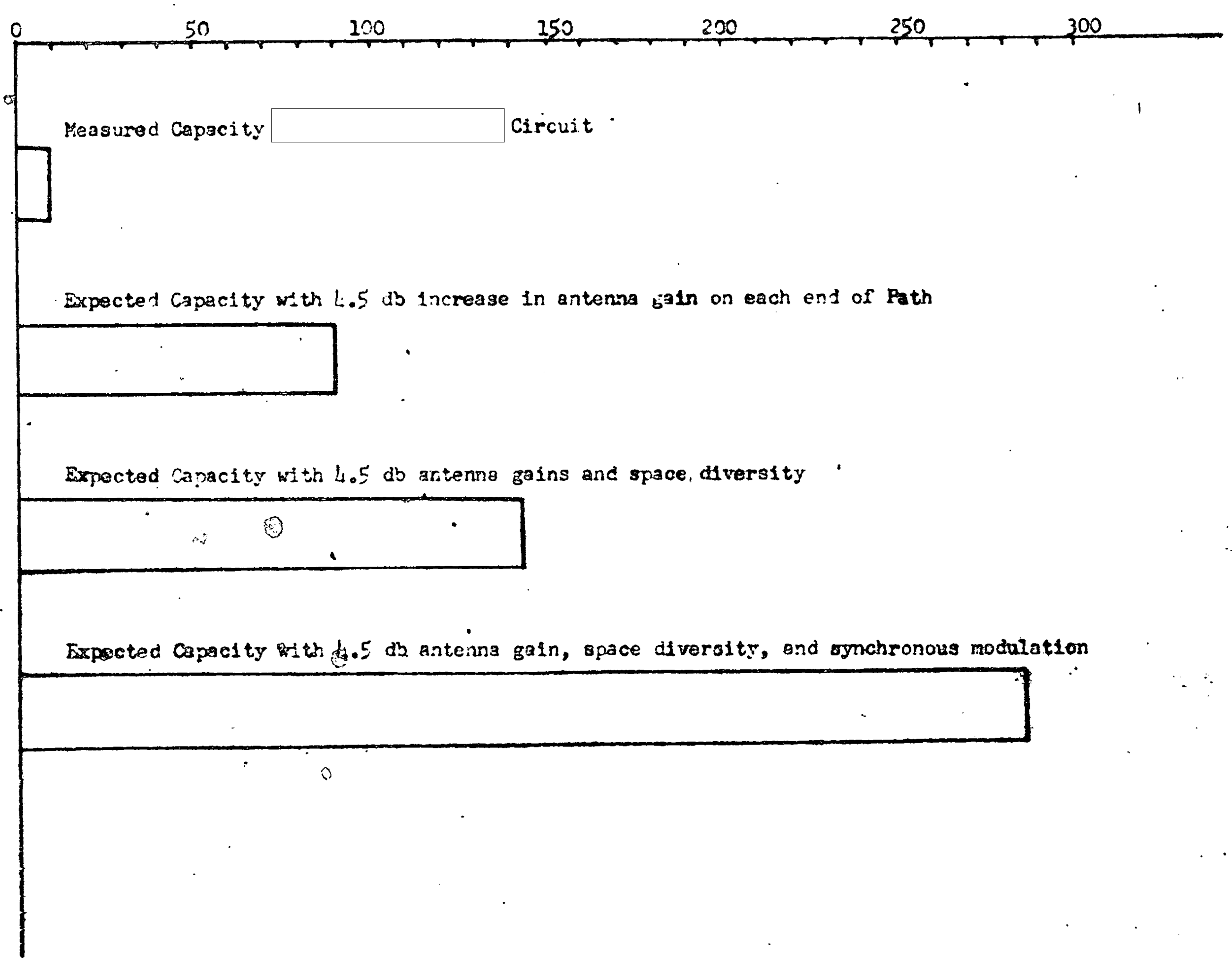

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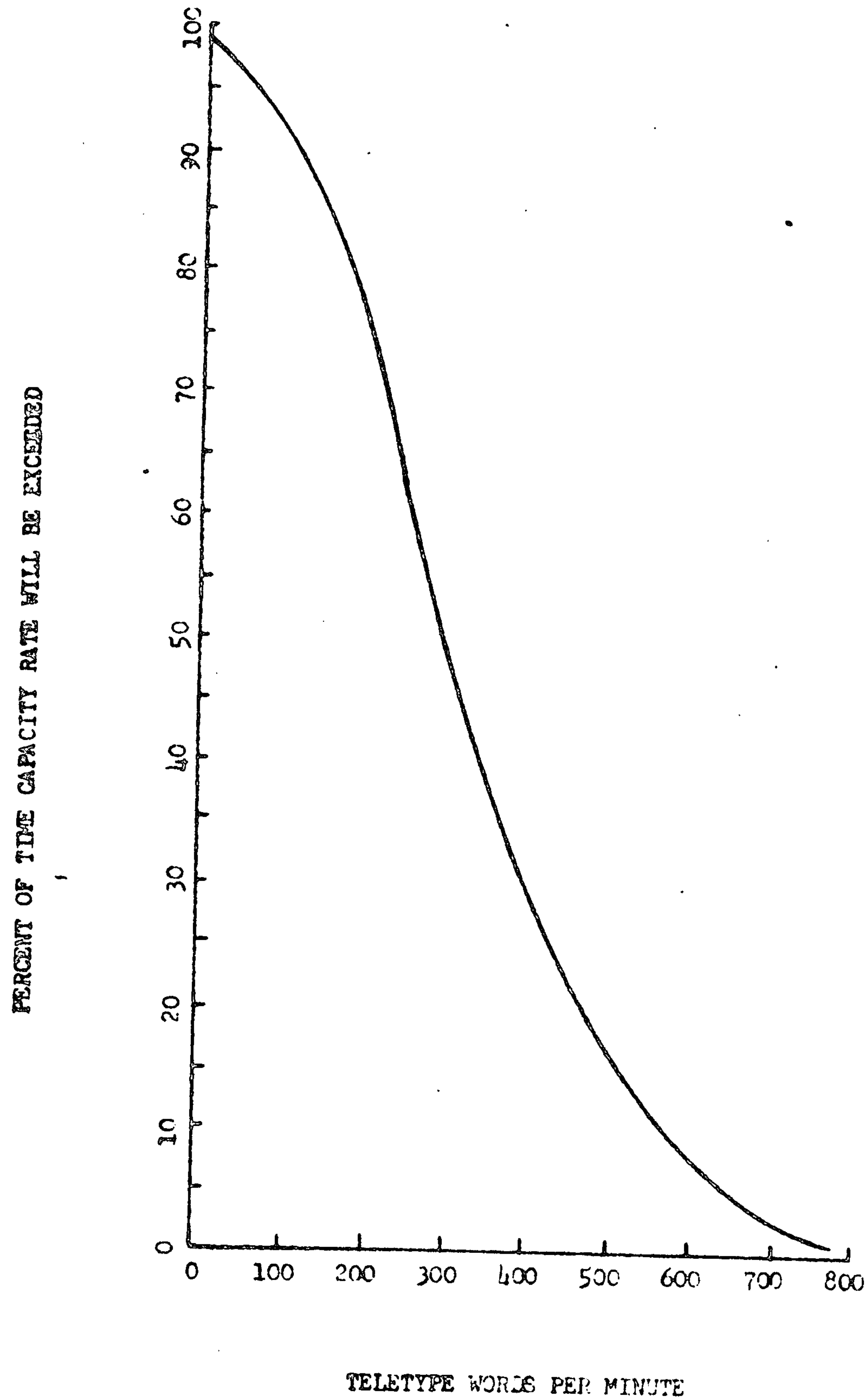
Illustration of Increased Traffic Capacity with Easy to Engineer Improvements

PERCENT OF TIME
CAPACITY RATE WILL BE EXCEEDED VS CAPACITY



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